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A ROTATIONAL STRAIN SEISMOMETER

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Abstract

A new type of rotational strain seismometer is designed to observe the rotational strain about the vertical axis.

Since the rotational strain about the vertical axis arises from SH type waves only, not from P and SV type waves, SH waves and Love waves may be picked up clearly from the complicated seismograms.

1. Introduction

The various kinds of seismometers have been constructed to observe the rotational movement caused by seismic waves, at a given point of the ground. And it seems that their sensitivities are not so high as to observe comparatively small movements.

In contrast to these earlier forms, the rotational strain seismometer measures the relative movements of different points, that is, the strain components of the ground caused by seismic waves.

By combining the shear strains in the horizontal plane, the rotational strain about the vertical axis which responds merely to SH type waves, can be obtained as will be described later. It is, therefore, expected that S and Love waves are to be recorded clearly without any disturbance from compressional waves.

The overall frequency response characteristic of the rotational strain seismometer depends merely upon the natural period and the damping constant of the galvanometer, since the instrument has no pendulum. In order to observe local earthquakes having epicentral distances less than about 200 km., a galvanometer with a period of 0.75 sec. was used for the observation.

2. Structure of the Instrument

A schematic representation of the instrument is shown in Fig. 1. Two

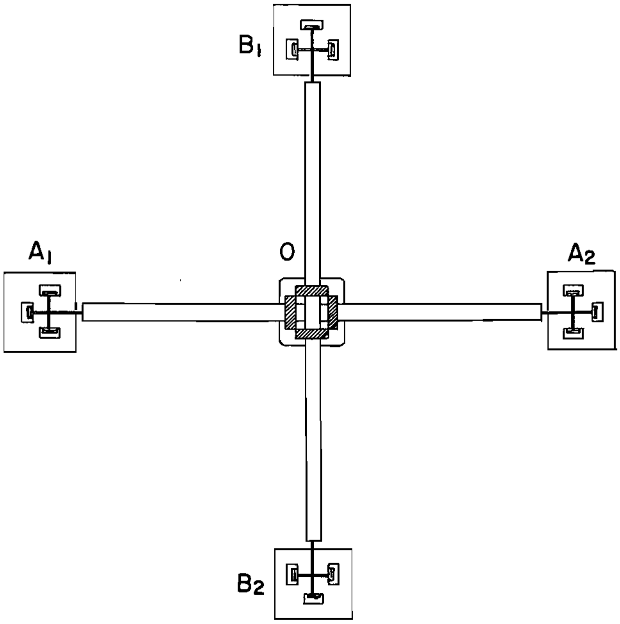


Fig. 1. Schematic representation of the rotational strain seismometer.

cylindrical iron rods of 10 cm. in diameter are rigidly fastened to the central pier 0, at right angles in the horizontal plane. Each end of the rods is equipped with three coils which are inserted in the gaps of magnets fastened to the other piers 2 meters apart from the central pier.

Strains of the ground caused by seismic waves are measured as changes of distance between coils and magnets which consist of an electrodynamic transducer of moving coil type. Two coils confronting to each other at an end of the rods generate an electromotive force (e.m.f.) proportional to the rate of change of the shear strains perpendicular to the rod. And the last one measures the linear strain parallel to the rod, which will be described in another paper.

The electrodynamic transducer is connected to the galvanometer for recording. When a higher sensitivity is required, a C-R amplifier may be used between the transducer and the galvanometer.

3. Theory of the Rotational Strain Seismometer

If the rod behaves as a rigid body the strains of the ground can be observed as relative movements of the neighbouring points of the gound, since the displacements of the piers caused by seismic waves are different from place to place.

The x and y axes are defined on the two rods perpendicular to each other at the undisturbed position and let u and v be the displacements of the ground in the directions of the x and y axes respectively.

If seismic waves propagate along the x axis and v_1, v_2 and v_0 are the y components of displacements of the piers A_1, A_2 and 0 respectively, the relative movements (v_1-v_0) and (v_2-v_0) are measured at the piers A_1 and A_2. Taking the difference of both, (v_1-v_2) can be observed as the shear strain $\left(\frac{\partial v}{\partial x}\right)$ between the piers A_1 and A_2. The other component of shear strain $\left(\frac{\partial u}{\partial y}\right)$ between the piers B_1 and B_2 is obtained in the same way. The rotational strain component about the vertical axis $\left(\frac{\partial v}{\partial x}-\frac{\partial u}{\partial y}\right)$ is also produced by using the shear strains.

Let α be the angle between the propagation direction of seismic waves and the x axis, and then the wave function is written as follows ;

$$\Phi=\Phi\left\{\frac{2\pi}{T}t-\frac{2\pi}{\lambda}(x\cos\alpha+y\sin\alpha)\right\}, \tag{1}$$

where T is the period of wave and λ is the apparent wave length at the earth's surface.

When Φ is the transverse wave of SH type, the horizontal displacements u and v are

$$\left.\begin{aligned} u &= -\Phi\sin\alpha \\ v &= \quad\Phi\cos\alpha \end{aligned}\right\} \tag{2}$$

Using the equations (1) and (2), the rotational strain component about the vertical axis (Ω_z) is given by

$$\begin{aligned}\Omega_z &= \frac{\partial v}{\partial x}-\frac{\partial u}{\partial y} \\ &= -\frac{2\pi}{\lambda}(\cos^2\alpha+\sin^2\alpha)\Phi'\left\{\frac{2\pi}{T}t-\frac{2\pi}{\lambda}(x\cos\alpha+y\sin\alpha)\right\},\end{aligned}$$

where

$$\Phi'=-\frac{\lambda}{2\pi}\frac{1}{\cos\alpha}\frac{\partial\Phi}{\partial x}=-\frac{\lambda}{2\pi}\frac{1}{\sin\alpha}\frac{\partial\Phi}{\partial y}=\frac{T}{2\pi}\frac{\partial\Phi}{\partial t}$$

Hence

$$\Omega_z = -\frac{2\pi}{\lambda}\Phi' = -\frac{T}{\lambda}\frac{\partial\Phi}{\partial t} = -\frac{1}{c}\frac{\partial\Phi}{\partial t}, \tag{3}$$

where c is the apparent wave velocity at the earth's surface.

It is evident from equation (3) that the directional response characteristic of the rotational strain seismometer remains constant with respect to the propagation direction of seismic waves, since Ω_z is independent of α.

On the other hand, for P waves Ω_z is given by

$$\Omega_z = \frac{1}{c}(\cos\alpha\cdot\sin\alpha - \cos\alpha\cdot\sin\alpha)\frac{\partial\Phi}{\partial t} = 0. \tag{4}$$

It is also apparent that Ω_z vanishes for SV type waves which never produce any horizontal shear strain. Thus the ratational strain about the vertical axis arises merely from SH type waves.

If the proper motions of the rods can be negrected and the seismic wave length λ is long in comparison to the length of the rod l, Ω_z and α are substantially constant over the interval l. And hence the sum of the rotational strain over the interval l may be written as follows ;

$$\xi = \int_0^l \Omega_z dx = -\frac{2\pi}{\lambda}\cdot\Phi'\cdot l = -\frac{l}{c}\frac{\partial\Phi}{\partial t} \tag{5}$$

The e.m.f. induced in the transducer coil is

$$E = k\frac{\partial\xi}{\partial t} = -\frac{k\cdot l}{c}\frac{\partial^2\Phi}{\partial t^2}, \tag{6}$$

where k is a constant.

It is clear from equation (6) that the e.m.f. responds to the velocity of the apparent surface waves which is indentical with the true velocity in the case of surface waves such as Love waves.

4. Calculation of Ω_z from Horizontal Displacements

When the horizontal displacements of neighbouring four points of the ground arranged on a square are obtained, the rotational strain about the vertical axis may be produced by the method as was described in the preceding section.

Four horizontal pendular seismometers named A, B, C and D are set on the square of a side of 20 cm., 15 meters apart from a concrete block about 500 kg. in weight which is hammered horizontally to generate SH type waves.

Sassa's C-type horizontal pendulums with a natural period of 0.5 sec. and San'ei-type galvanometers with a natural period of 1/30 sec. are used for the observation.

Fig. 2 is an example of the traces of the horizontal and the rotational

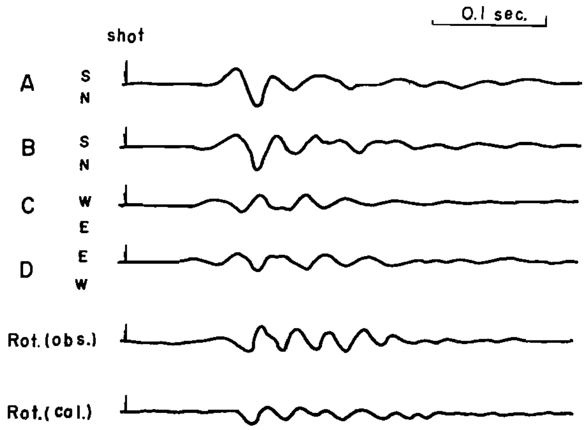


Fig. 2. An example of traces of the horizontal and the rotational strain components obtained by the experiment.

strain components obtained by the experiment. Rot (cal.) is produced from the relative horizontal displacements by using the same method, and Rot (obs.) is also calculated by an electric circuit which will be shown in the next section.

The comparison of the traces shows that the wave forms of Rot (cal.) and Rot (obs.) are substantially identical. It is, therefore, evident that the electric circuit is available for calculation of the rotational strain of the ground.

5. Frequency Response Characteristic Curve

The differential equation of the galvanometer connected to the transducer coil is given by

$$\frac{d^2\theta}{dt^2}+2\varepsilon\frac{d\theta}{dt}+n_0{}^2\theta=\frac{g}{I\cdot R}E, \qquad (7)$$

where

θ : Angular deflection of galvanometer,

ε : Damping coefficient,

n_0 : $\frac{2\pi}{T_0}$, T_0 : Natural period of galvanometer,

g : Electrodynamic constant of galvanometer,

I : Moment of inertia of galvanometer and

R : Total resistance of coils and galvanometer.

The linear deflection on the recording paper is

$$s=a\cdot\theta, \tag{8}$$

where a is the arm length of galvanometer. Using equations (6) and (8), equation (7) is rewritten as follows ;

$$\frac{d^2s}{dt^2}+2\varepsilon\frac{ds}{dt}+n_0{}^2s=-V\frac{\partial^2\Phi}{\partial t^2}, \tag{9}$$

where $V=(g\cdot k\cdot l\cdot a)/(I\cdot R\cdot c)$.

If $\Phi=b\cdot\sin n\left(t-\frac{r}{c}\right)$, equation (9) is identical with the equation of the pendular seismometer and the stationary state solution is immediately given by

$$s=\frac{V}{\sqrt{(1-u^2)^2+4h^2u^2}}b\cdot\sin\left\{n\left(t-\frac{r}{c}\right)+\delta\right\}, \tag{10}$$

where $r=x\cos\alpha+y\sin\alpha$,

$u=n_0/n=T/T_0$, T : period of seismic wave,

$h=\varepsilon/n_0$, $\tan\delta=(2hu)/(u^2-1)$.

When the damping constant of the galvanometer is critical ($h=1.0$), the solution is given by

$$s=\frac{V}{1+u^2}b\cdot\sin\left\{n\left(t-\frac{r}{c}\right)+\delta\right\}. \tag{11}$$

In order to gain a higher magnification, a C-R amplifier was used between the transducer and the galvanometer. The circuit diagram of the amplifier is shown in Fig. 3.

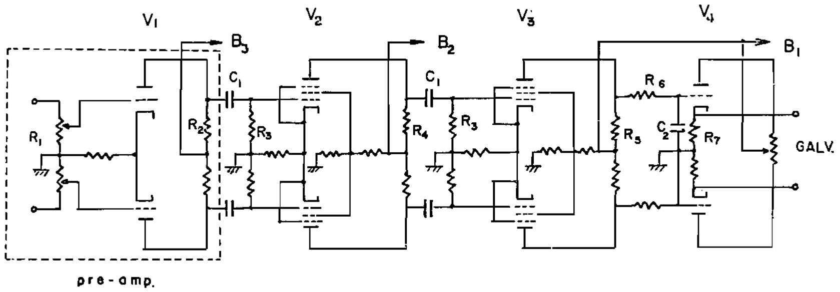
The resulting frequency response characteristic curve of the rotational strain seismometer is, therefore, drawn by multipling $1/(1+u^2)$ by the frequency response of the amplifier.

If D is the deflection of galvanometer on the recording paper in cm. for a unit current, the static magnification is

$$V=\frac{4\pi^2}{T_0{}^2}\frac{k\cdot l}{R\cdot c}\cdot D, \tag{12}$$

where

$$D=\frac{T_0{}^2}{4\pi^2}\frac{g}{I}\cdot a.$$



$C_1 =$ 1 μfd	$V_3 =$ 6AU6
$C_2 =$ 0.5 μfd	$V_4 =$ 12AU7
$R_1 =$ 100 kΩVR	$V_5 =$ 6SN7
$R_2 =$ 100 kΩ	$V_6 =$ 2A3
$R_3 =$ 2 MΩ	$V_7 =$ 6SJ7
$R_4 =$ 150 kΩ	$V_8 =$ 80
$R_5 =$ 50 kΩ	$V_9 =$ VR-150
$R_6 =$ 500 kΩ	$B_1 = +200$V
$R_7 =$ 20 kΩ	$B_2 = +145$V
$V_1 =$ 12AX7	$B_3 = +135$V
$V_2 =$ 6AU6	

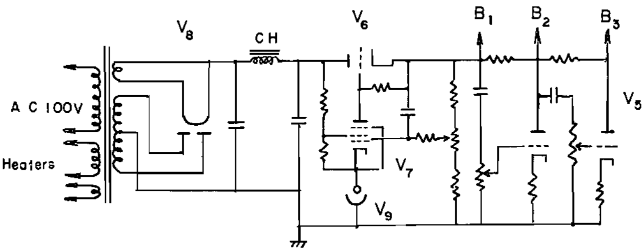


Fig. 3. Circuit diagram of the amplifier of which pre-amplifier consists of four channels.

Let V_0 be the magnification of the amplifier measured at a period of 0.75 sec. and then

$$V_0 \cdot \frac{4\pi^2}{T_0^2} \cdot \frac{k}{R} \cdot D = 250{,}000$$

is obtained from a simple practical measurement, where T_0 is 0.75 sec..

Hence the resulting static magnification V_1 is

$$V_1 = V \cdot V_0 \fallingdotseq 250{,}000 \times \frac{2\times10^2}{5\times10^5} = 100,$$

where $l = 2\times10^2$ cm., and if $c \fallingdotseq 5\times10^5$ cm./sec..

In conclusion the coefficient of magnification $1/(1+u^2)$ and the overall frequency response characteristic curve are drawn as shown in Fig. 4.

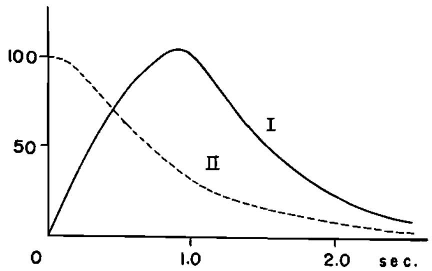


Fig. 4. I : Overall frequency response curve of the rotational strain seismometer consisting of the transducer shown in Fig. 1 and the amplifier shown in Fig. 3.
II The coefficient of magnification without the amplifier : $1/(1+u^2)$.

6. Seismograms

The rotational strain seismometer was constructed and set up at Kyoto on February 1958 and shifted thereafter to Abuyama Seismological Observatory in order to get rid of the extremely severe disturbance of the ground unrests, especially from the artificial noise sources, in the day time at Kyoto.

As expected from the frequency response characteristic and the SH response characteristic of the seismometer, near earthquakes of shallow foci have mainly been recorded.

The following seismograms are compared with the horizontal seismograms for identification of S and Love waves.

a) The earthquake of March 7, 1958, 11^h30^m.

The earthquake occurred at the south part of Kii Channel, Central Honshu, and its seismograms are shown in Fig. 5. The upper record (Rot.)

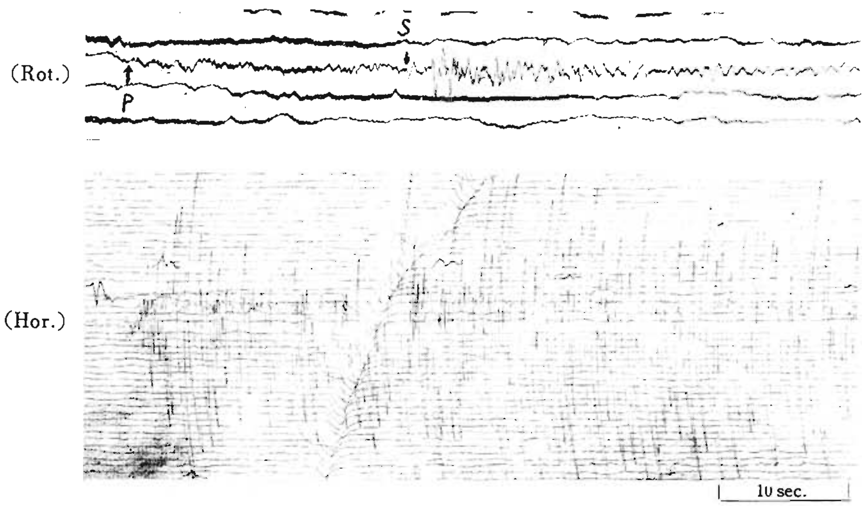


Fig. 5. Comparision of traces of the earthquake, March 7, 1958, 11^h30^m. The upper record is the rotational strain component observed at Kyoto and the lower is the horizontal (NS) component observed at Abuyama.

is the rotational strain component observed at Kyoto ($\Delta=160$ km. ca.) and the lower record (Hor.) is obtained by the horizontal short period electromagnetic seismometer ($T_0=1.0$ sec., $h_0=1.0$: $T_g=0.7$ sec., $h_g=0.8$) used for the routine operation at the observatory ($\Delta=140$ km. ca.). Since the theoretical frequency responses of the two instruments are similar to each other, comparison of the trains is very convenient.

In the trace of (Rot.), the S and Love waves are recorded very clearly, and it is very interesting to note that the wave forms of S and Love waves are comparatively simple and pulse-like and also the minor phases between initial P and S phases are, on the other hand, obscure as expected for the zero response to P waves of the instrument. On the basis of this fact it is ascertained that the SH type waves are picked up from the complicated wave train by the instrument.

b) The local earthquake of February 4, 1959, 12^h18^m

The local shocks of shallow foci have been frequently observed with distinct S phases at the observatory. As shown in Fig. 6 the two traces are

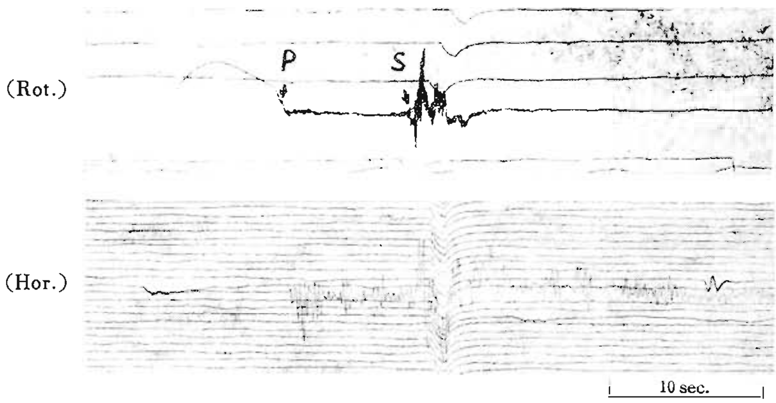


Fig. 6. Comparison of traces of the local earthquake of Feb. 4, 1959, 12^h18^m. The upper record is the rotational strain component and the lower is the horizontal (NS) component observed at Abuyama.

substantially identical except for P and the minor phases. For more precise analyses of the S part of the traces, the orbital motion is drawn from the records of Sassa type horizontal seismometers (S-1,000) with a period of 1.2 sec..

In the traces of S waves and the orbital motion shown in Figs. 7 and 8 respectively, 0_s coincides with the clear S phase of the rotational strain component shown in Fig. 6. Even in the case of reading the comparatively simple records such traces as shown in Fig. 7, the initial S phase on the record (for instance, E-W component) may be some times misidentified.

If it is recognized that the orbital motion of S waves is substantially linear and SH and SV waves arrive at the observing station simultaneously

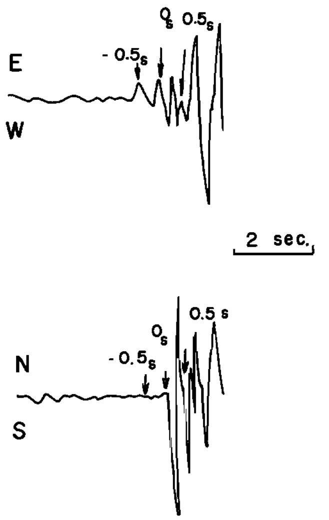


Fig. 7. S wave traces of the earthquake shown in Fig. 6, obtained by S-1,000 horizontal seismometers at Abuyama.

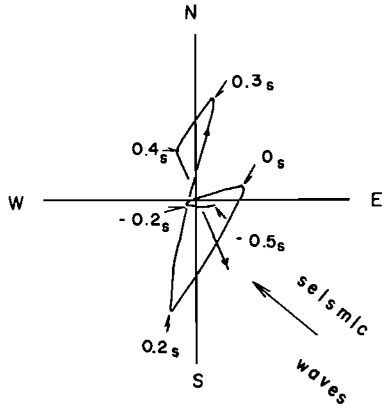


Fig. 8. Orbital motion of S waves obtained from the traces of Fig. 7. 0_s coincides with the S phase of the rotational strain component shown in Fig. 6.

as shown in a study of O. W. Nuttli (1959), the initial S wave is indicated by 0_s in Figs. 7 and 8, which is identical with the clear S wave of the rotational strain component.

c) Love wave train from a severe earthquake.

In the present analysis we used the records of a shock of M 7 occurred at the near coast of N-E Honshu on March 20, 1960, $17^h07^m26^s$

A continuous train of surface waves with period 13 to 48 sec. was clearly recorded by the rotational strain seismometer as may be seen from the seismogram in Fig. 9. By using the records of (S-1) seismometers ($T_0=30$ sec., $h_0=0.8$) shown in Fig. 10, the orbital motion in the horizontal plane

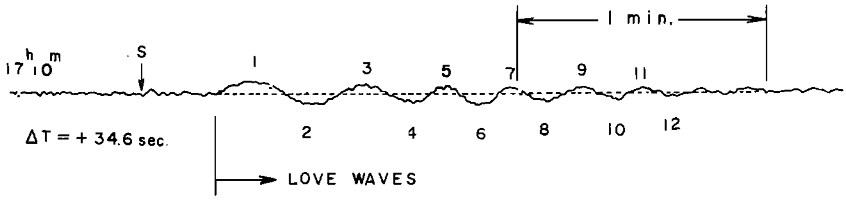


Fig. 9. Love wave train of the earthquake of March 20, 1960, 17^h07^m ($\Delta \fallingdotseq 990$ km., $M \fallingdotseq 7$) recorded by the rotational strain seismometer.

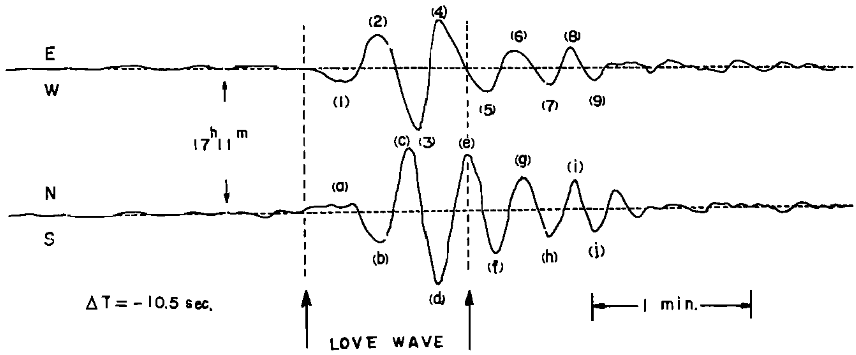


Fig. 10. Surface wave group of the earthquake shown in Fig. 9 obtained by S-1 horizontal seismometers.

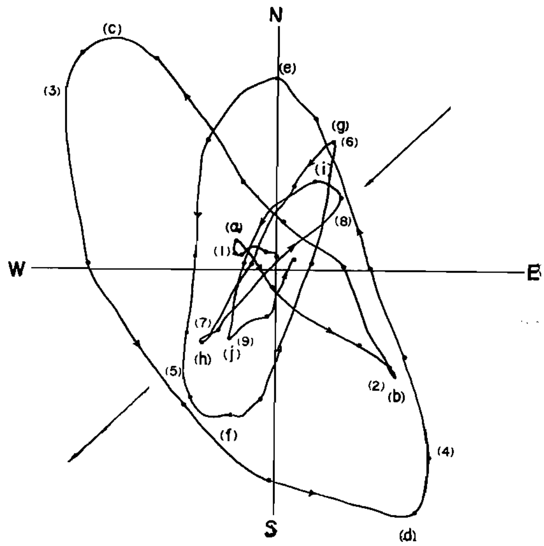


Fig. 11. Orbital motion in the horizontal plane plotted from the traces of Fig. 10.

is plotted in Fig. 11.

It is evident from Figs. 10 and 11 that the first part of the wave trains indicated by arrows in Fig. 10 is the fundamental Love waves followed by Rayleigh type waves, since the peaks and the troughs lettered by (1)-(4) and (a)-(d) oscillate transversally to the direction of wave propagation and thereafter the oscillations in the horizontal plane are in the plane of the seismic ray.

The arrival times of the peaks and the troughs read from the records of Figs. 9 and 10 are plotted in Fig. 12 where the ordinate is the phase angle for the rotational strain component in cycle. The arrival time curve for the rotational strain component coincides reasonably well with that of the horizontal wave trains in the interval of Love wave. After that, these curves show different tendencies which may be regarded as the superposition of Rayleigh waves.

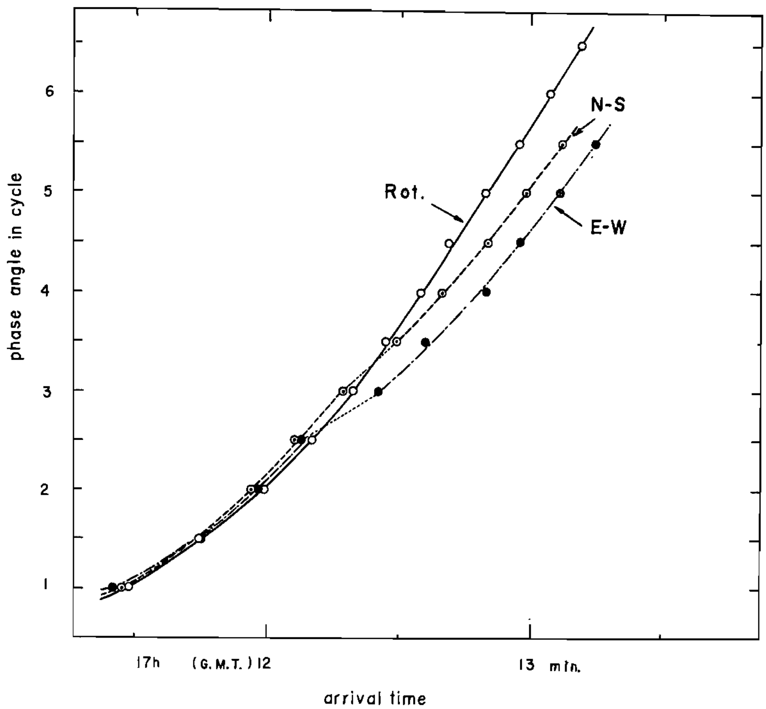


Fig. 12. Arrival time curves for the rotational strain component and the horizontal components. The ordinate is the phase angle in cycle for the Love wave train shown in Fig. 9.

Thus a continuous train of Love waves was picked up undisturbed by other waves, as expected for the SH response characteristic of the instrument. The periods of the peaks and the troughs of the Love waves are determined from the slope of the arrival time curve. Group velocities are also measured roughly by using $t_m = \frac{\Delta}{u} + t_0$, where t_m and t_0 are the arrival time of m-th peak or trough and the origin time respectively, and the epicentral distance Δ is about 990 km..

Thus a dispersion curve of Love waves covering the period range 13 to 48 sec. was calculated and plotted in Fig. 13 with the theoretical curves for the purely oceanic and continental paths given by W.M. Ewing et al. (1957). The observed curve falls between the limited cases except for periods less than 20 sec. as expected from the fact that the Love waves travelled through a mixed path across the boundary of the Pacific Ocean basin.

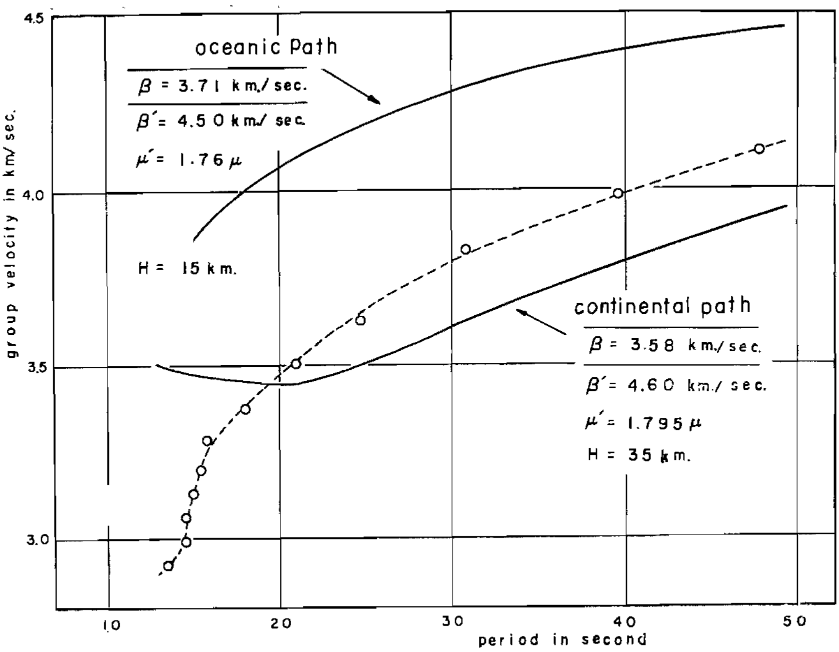


Fig. 13. Observed group velocities with the group velocity curves of Love wave for the purely oceanic and continental paths given by W.M. Ewing et al. (1957).

Several possibilities of explaining the low velocities in the periods less than 20 sec. have been discussed considering the refraction, reflection, scattering and so on, but the many attempts seem to have failed in fitting the observations on these simple assumptions. Therefore, it appears that more observations are required to explain the low velocities of the shorter period Love waves.

7. Summary

A linear strain seismograph was first successfully utilized for routine operation by H. Benioff (1935) using a highly sensitive electrodynamic transducer. Here, a highly sensitive rotational strain seismometer was designed tentatively by adopting a moving coil type transducer and a C-R amplifier.

As described in the preceding sections the rotational strain component about the vertical axis responds merely to SH type waves. And hence the undisturbed Love waves may be clearly picked up and a simple behavior of

SH waves both at the earth's surface and at the interfaces of layers can be effectively studied.

More advantages of the rotational strain seismometer when compared with that of simple pendular seismometers are ;

1) The directional response of the instrument remains constant with respect to the propagation direction of the waves and then the transducer part of the instrument can be equipped in a voluntary direction.

2) The frequency response characteristic varies by merely exchanging galvanometers or amplifiers.

3) The instrument never responds to the ground-tilt.

8. Acknowledgement

At the conclusion of this report the writer wishes to express his deep gratitude to Prof. K. Sassa for his valuable suggestions and kind instruction. His cordial thanks are also due to Prof. H. Miki and Dr. K. Okano for their encouragements.

The writer is greatly indebted to Messrs. K. Morimoto, T. Kobayashi and J. Saida for their helpful assistance in constructing the seismometer.

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